Processes

CSE 351 Autumn 2017

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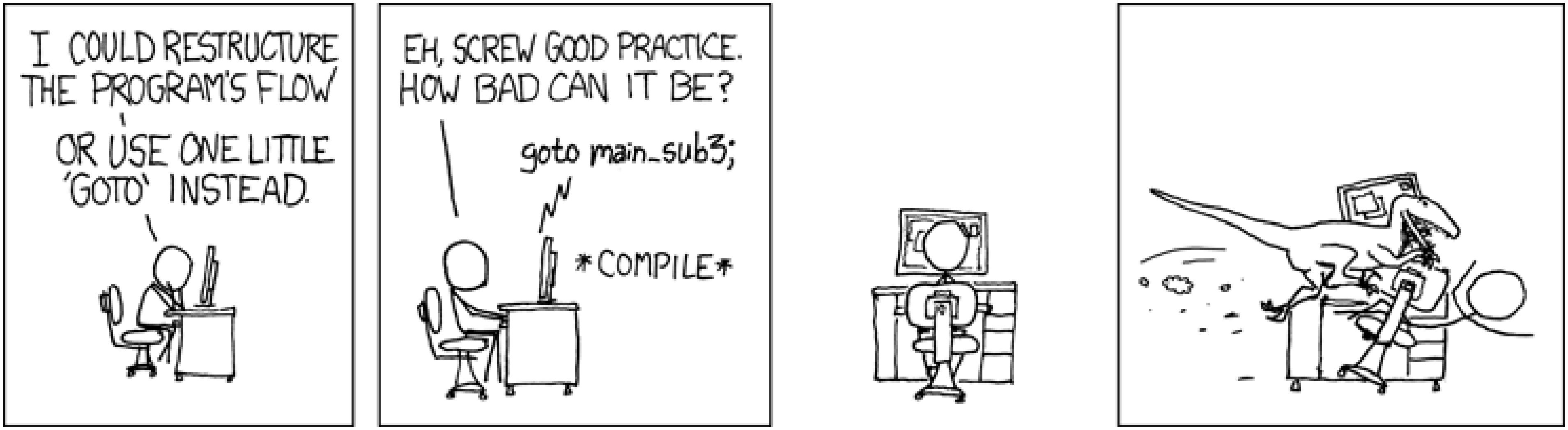

I COULD RESTRUCTURE THE PROGRAM'S FLOW OR USE ONE LITTLE 'GOTO' INSTEAD.
EH, SCREW GOOD PRACTICE. HOW BAD CAN IT BE?
goto main_sub3;
COMPILE

http://xkcd.com/292/

Administrivia

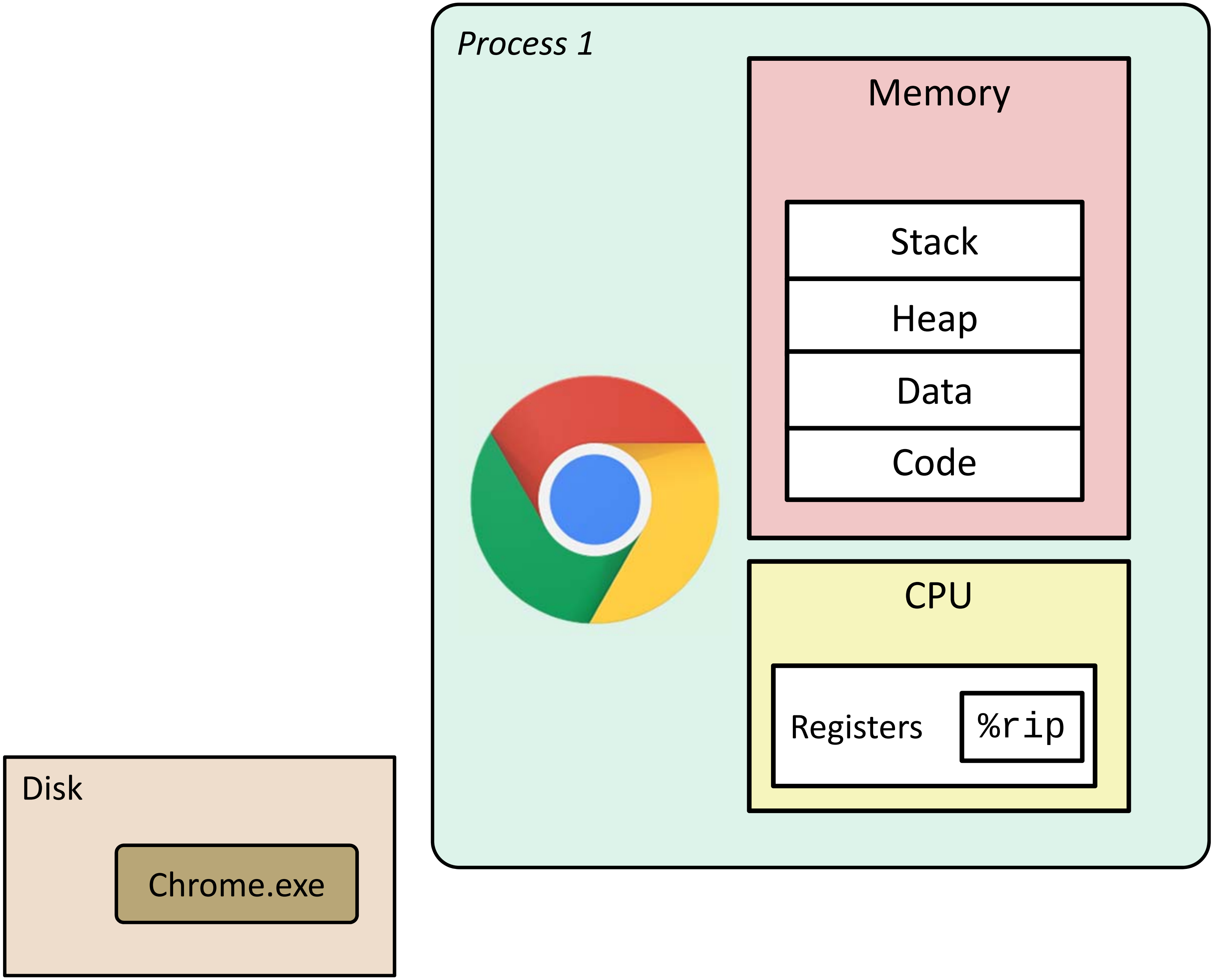
- Homework 4 due Friday (11/17)
- Lab 4 due after Thanksgiving (11/27)
  - Parts of this lab are new, so don’t hesitate to ask if anything is unclear or seem buggy!

Processes

- **Processes and context switching**
- Creating new processes
  - `fork()`, `exec*()`, and `wait()`
- Zombies

What is a process?

It's an *illusion*!



Process 1

Memory

Stack

Heap

Data

Code

CPU

Registers `%rip`

Disk

Chrome.exe

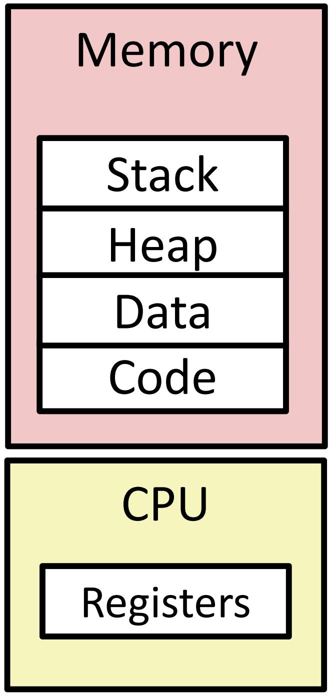
What is a process?

- Another *abstraction* in our computer system
  - Provided by the OS
  - OS uses a data structure to represent each process
  - Maintains the ***interface*** between the program and the underlying hardware (CPU + memory)
- What do *processes* have to do with *exceptional control flow*?
  - Exceptional control flow is the *mechanism* the OS uses to enable **multiple processes** to run on the same system
- What is the difference between:
  - A processor? A program? A process?

    hardware the "blueprint" an instance

Processes

- A ***process*** is an instance of a running program
  - One of the most profound ideas in computer science
  - Not the same as "program" or "processor"
- Process provides each program with two key abstractions:
  - *Logical control flow*
    - Each program seems to have exclusive use of the CPU
    - Provided by kernel mechanism called ***context switching***
  - *Private address space*
    - Each program seems to have exclusive use of main memory
    - Provided by kernel mechanism called ***virtual memory***



Memory

Stack

Heap

Data

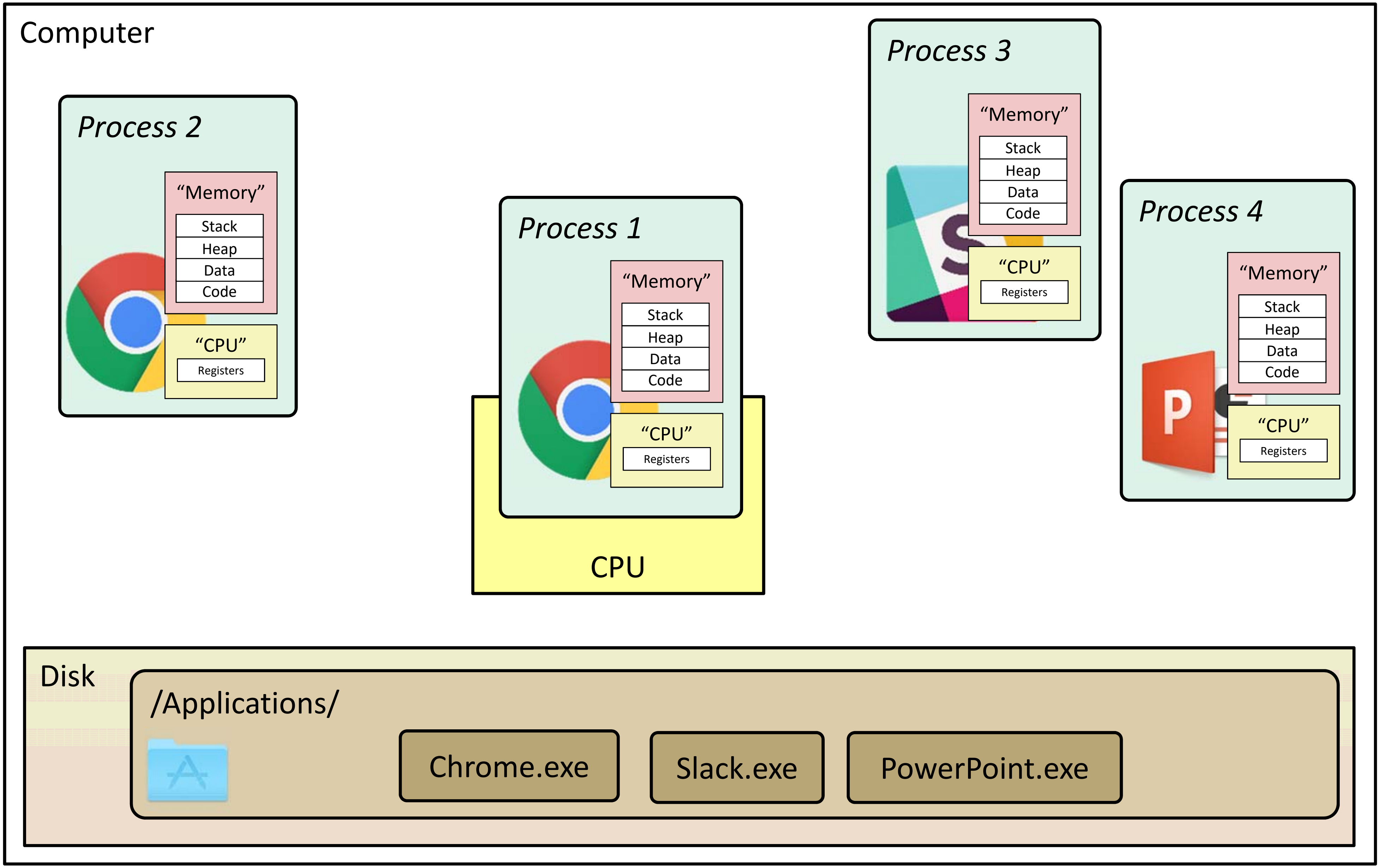
Code

CPU

Registers

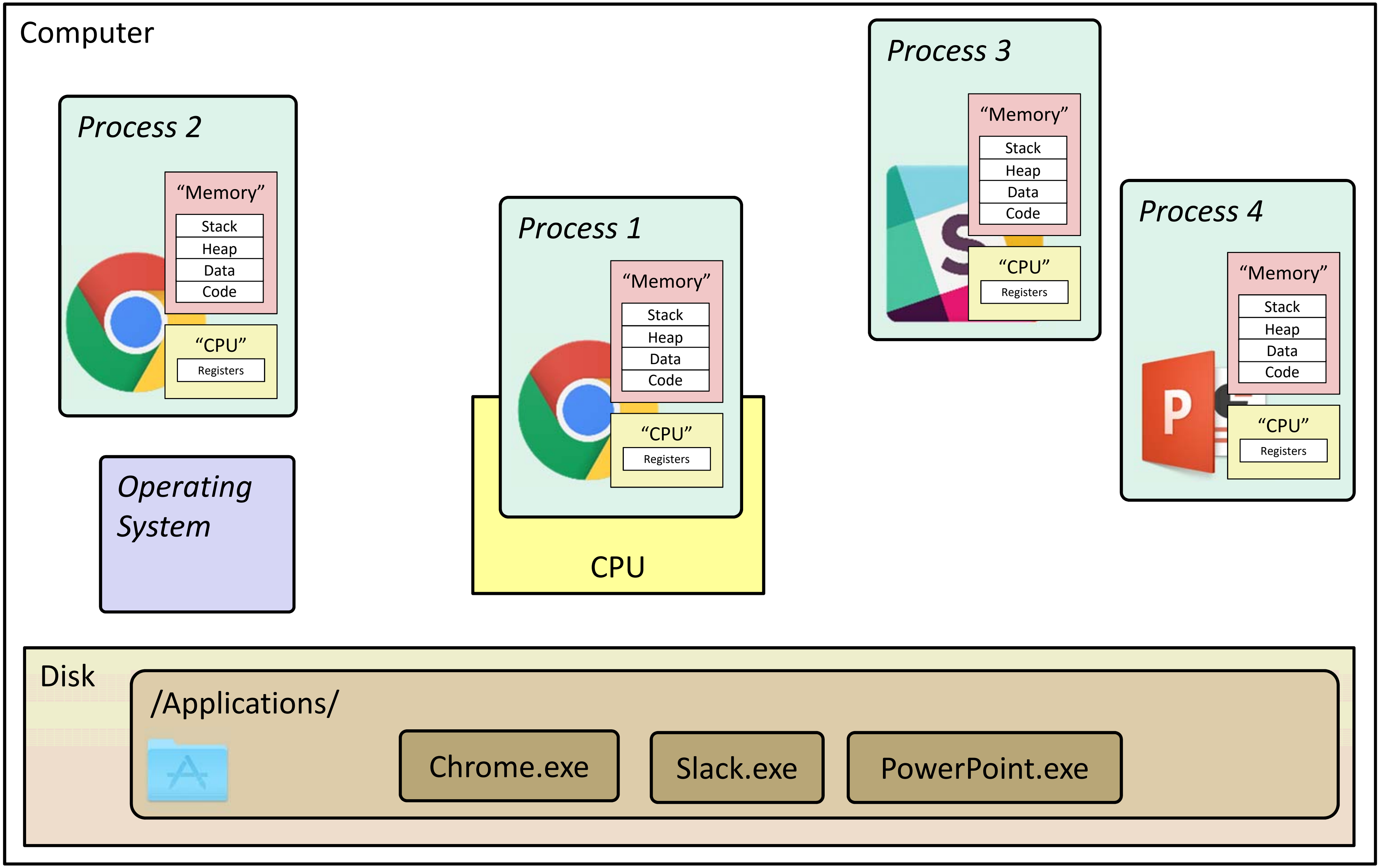
What is a process?

It's an *illusion*!

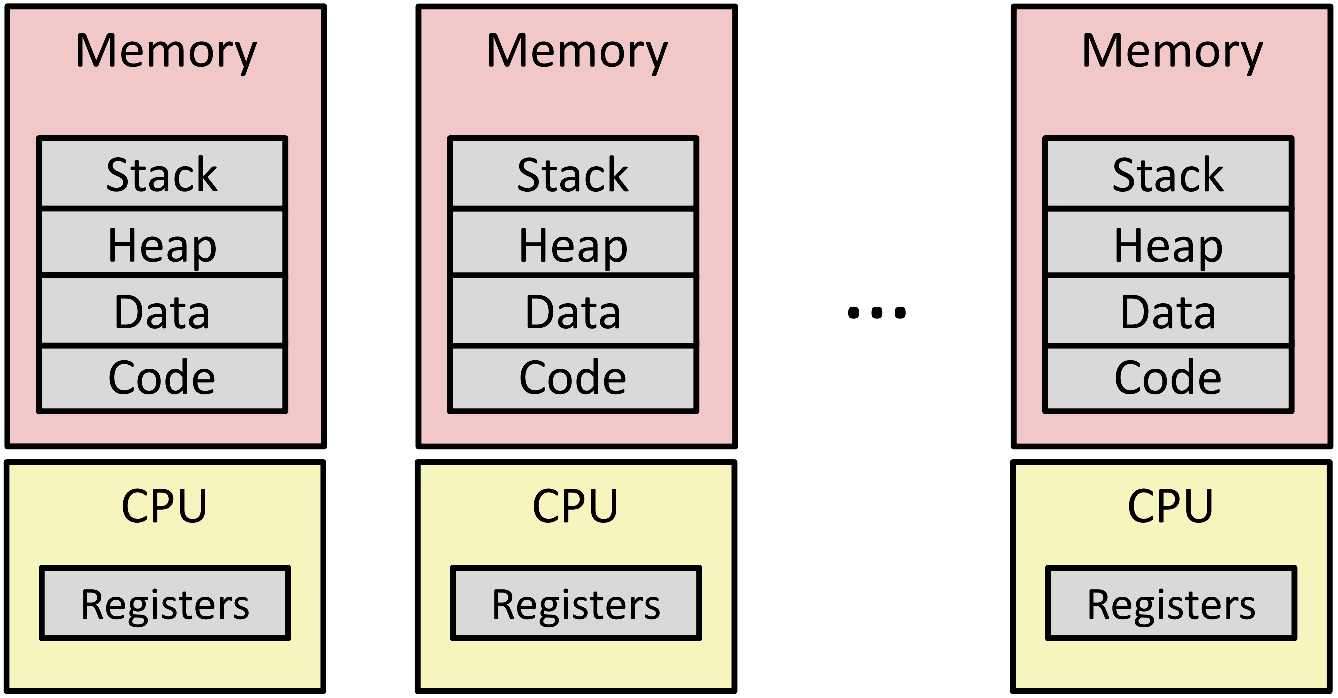


What is a process?

It's an *illusion*!



Multiprocessing: The Illusion

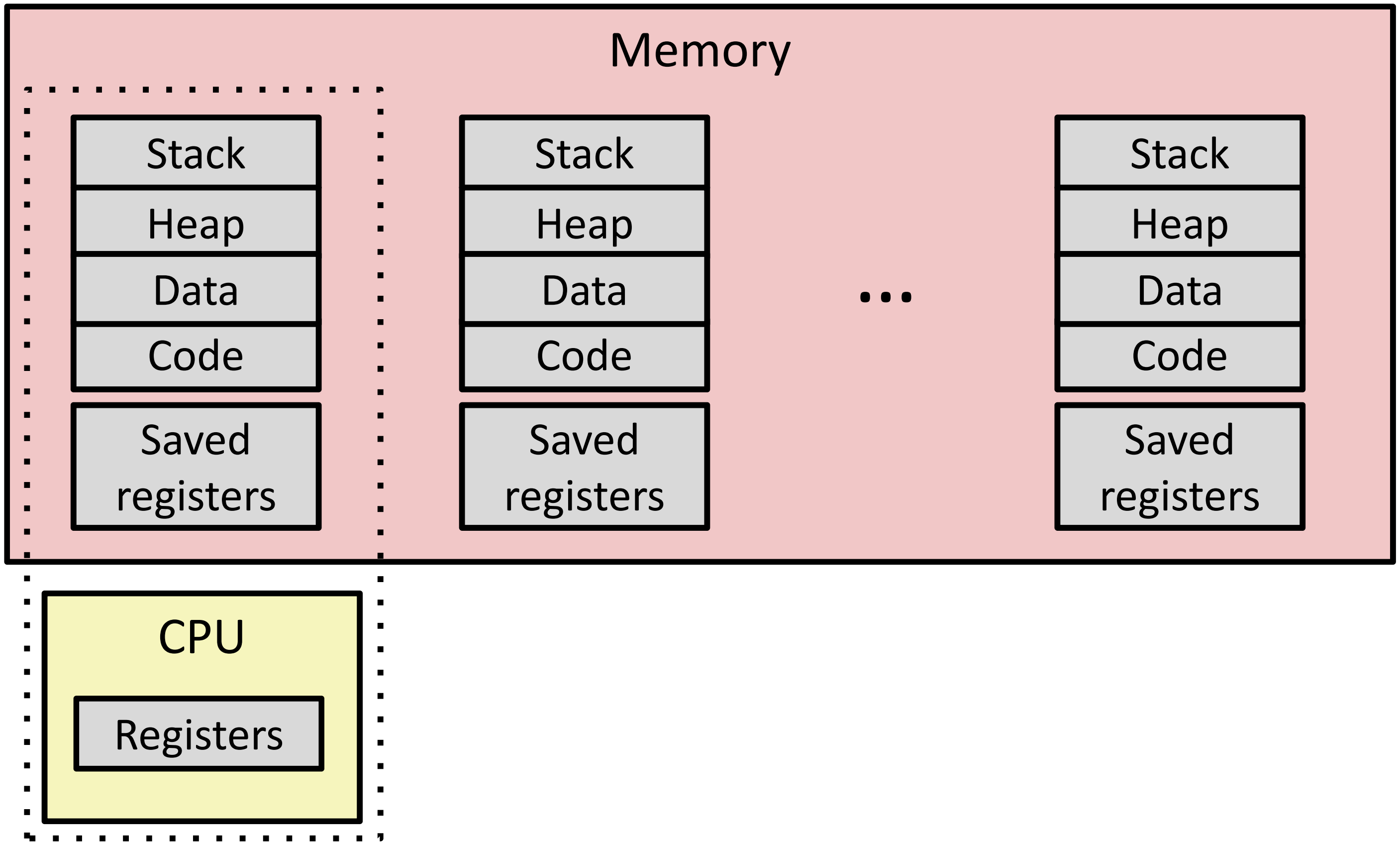


- Computer runs many processes simultaneously
  - Applications for one or more users
    - Web browsers, email clients, editors, …
  - Background tasks
    - Monitoring network & I/O devices

user-level

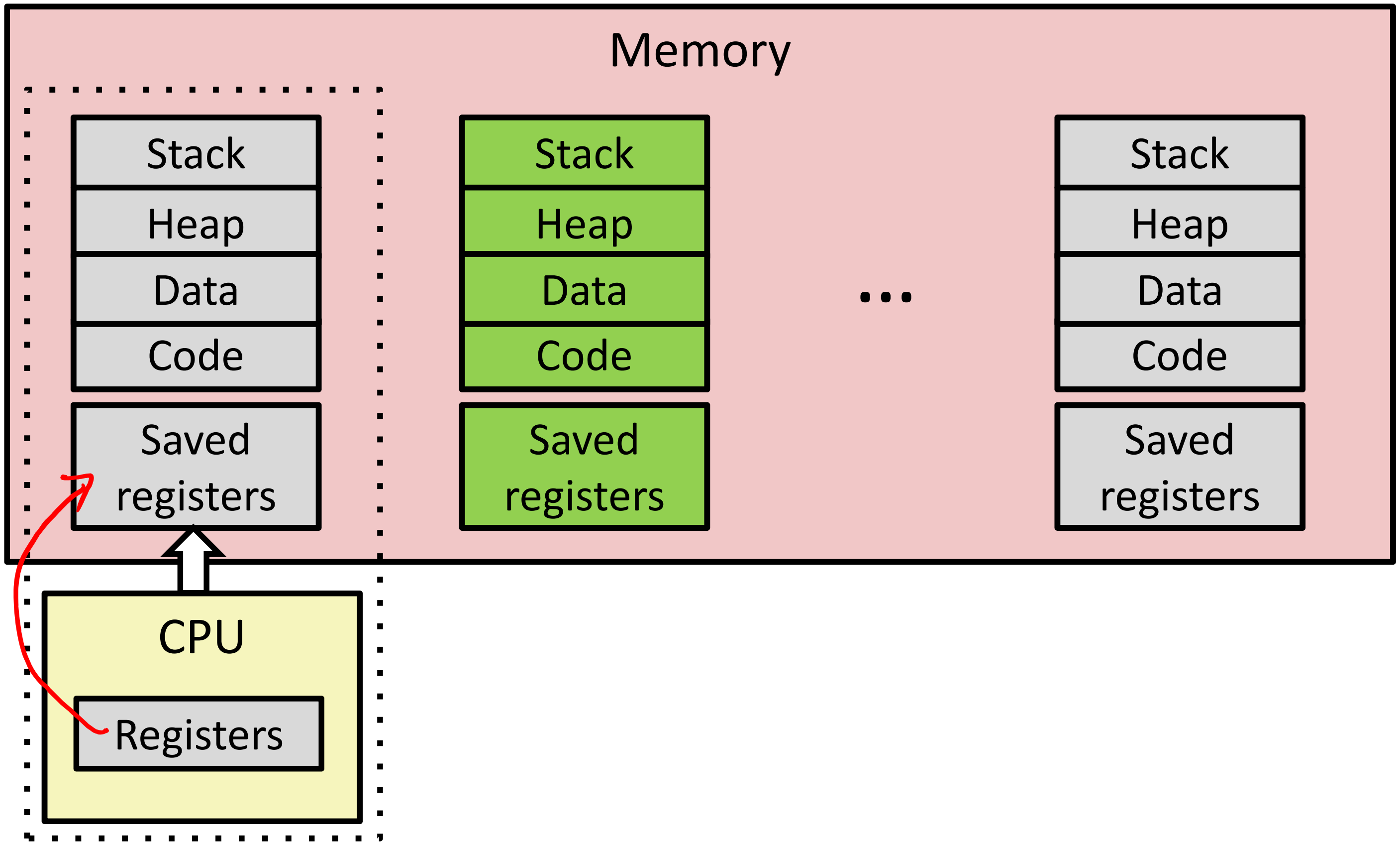
mostly kernel/OS - level

Multiprocessing: The Reality



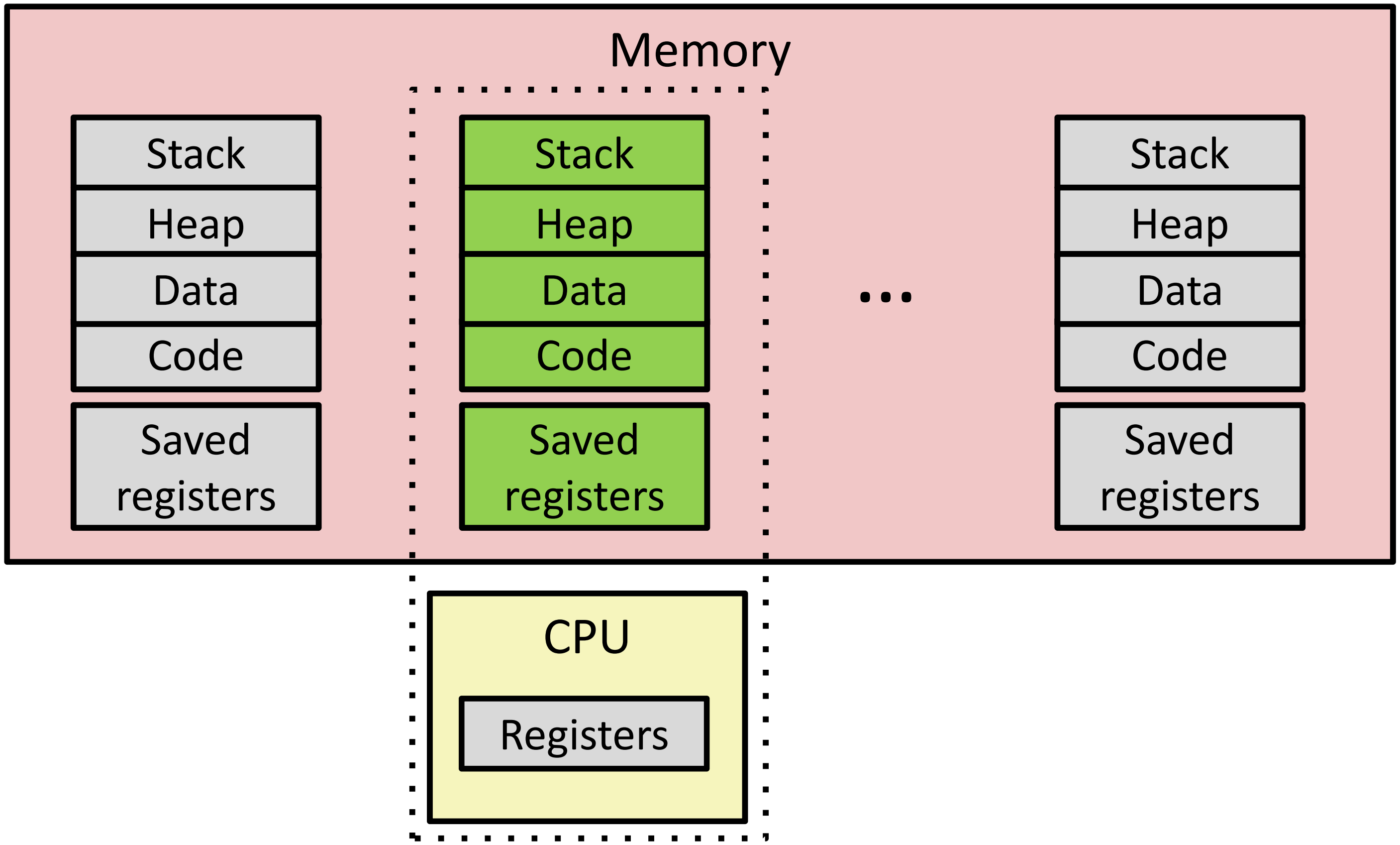
- Single processor executes multiple processes *concurrently*
  - Process executions interleaved, CPU runs *one at a time*
  - Address spaces managed by virtual memory system (later in course)
  - *Execution context* (register values, stack, …) for other processes saved in memory

Multiprocessing



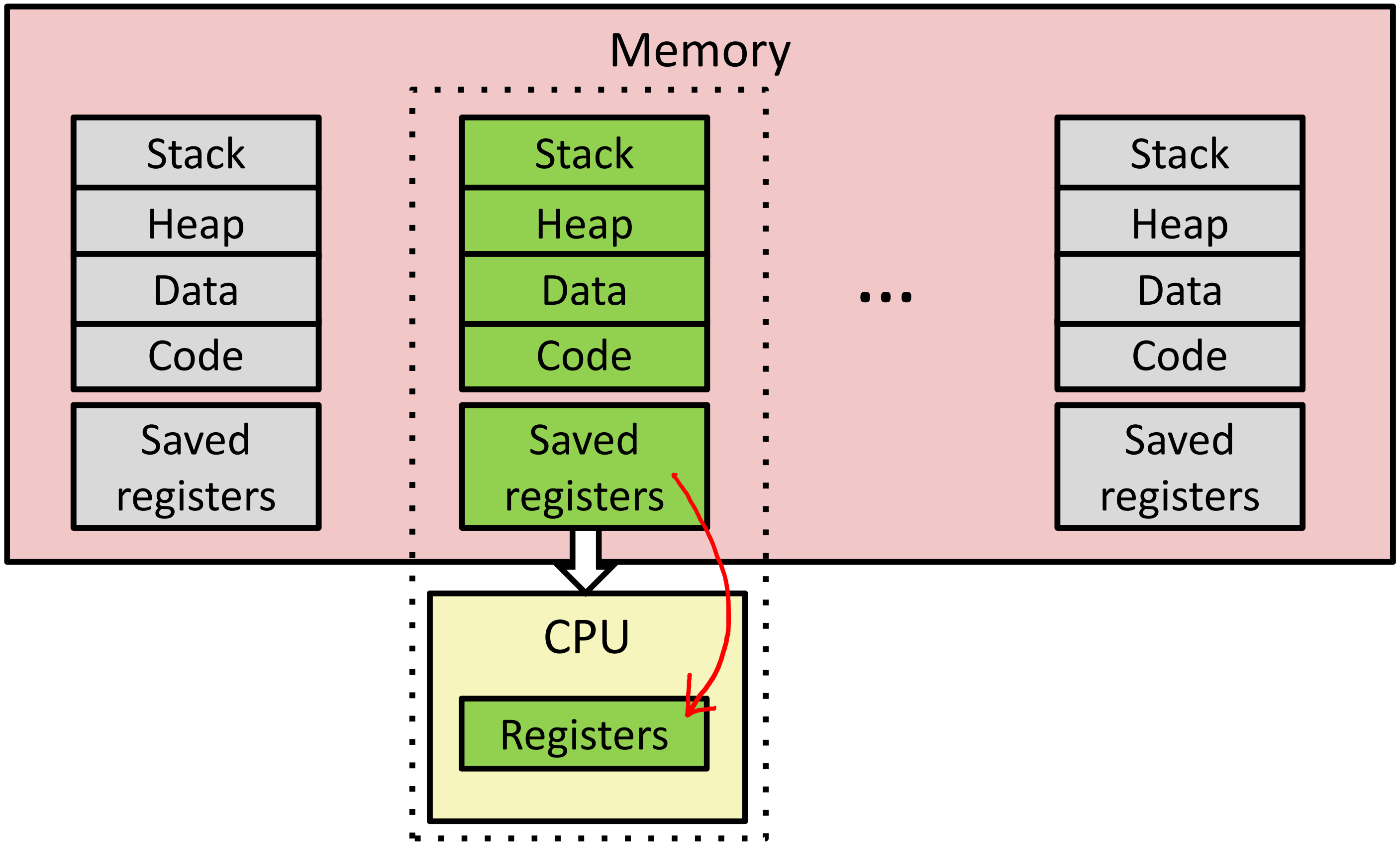
- Context switch
  1) Save current registers in memory

Multiprocessing



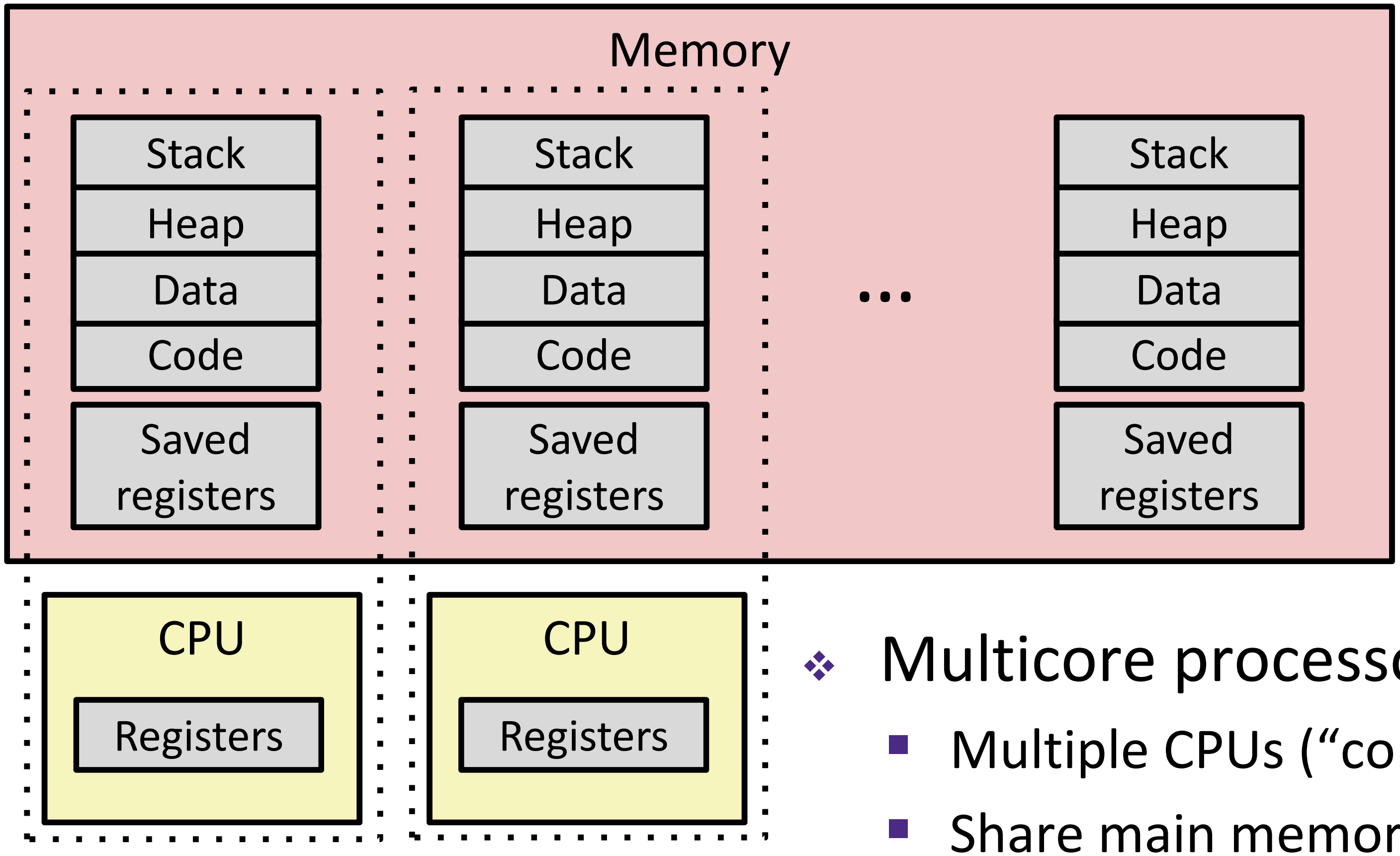
- Context switch
  1) Save current registers in memory
  2) **Schedule next process for execution** (OS decides)

Multiprocessing



- Context switch
  1) Save current registers in memory
  2) Schedule next process for execution
  3) **Load saved registers and switch address space**

Multiprocessing: The (Modern) Reality

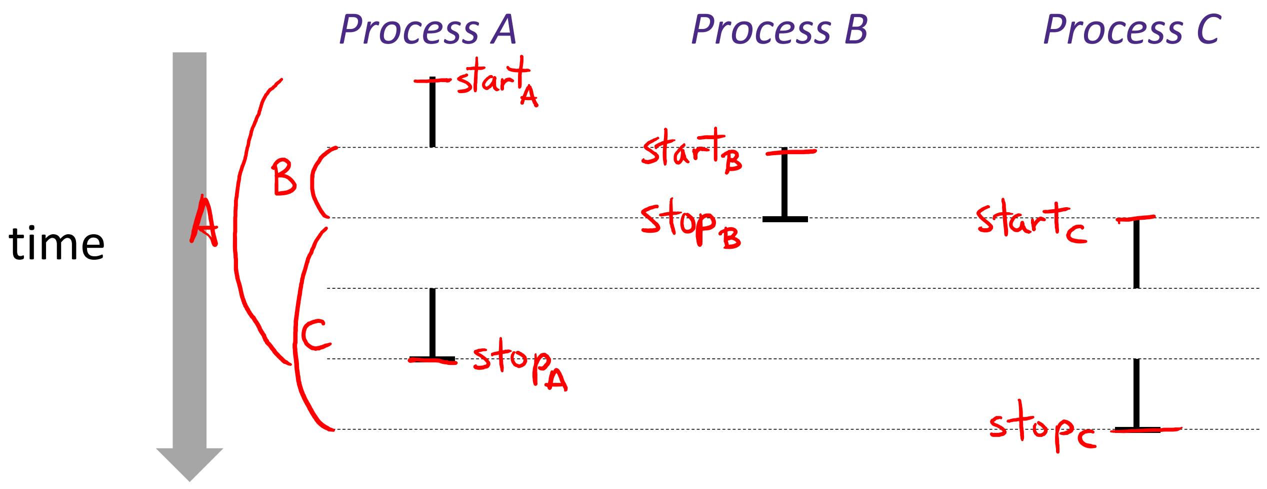


- Multicore processors
  - Multiple CPUs (“cores”) on single chip
  - Share main memory (and some of the caches)
  - Each can execute a separate process
    - Kernel schedules processes to cores
    - ***Still* constantly swapping processes**

Concurrent Processes

Assume only one CPU

- Each process is a logical control flow
- Two processes *run* *concurrently* (are concurrent) if their instruction executions (flows) overlap in time
  - Otherwise, they are *sequential*
- Example: (running on single core)
  - Concurrent: A & B, A & C
  - Sequential: B & C

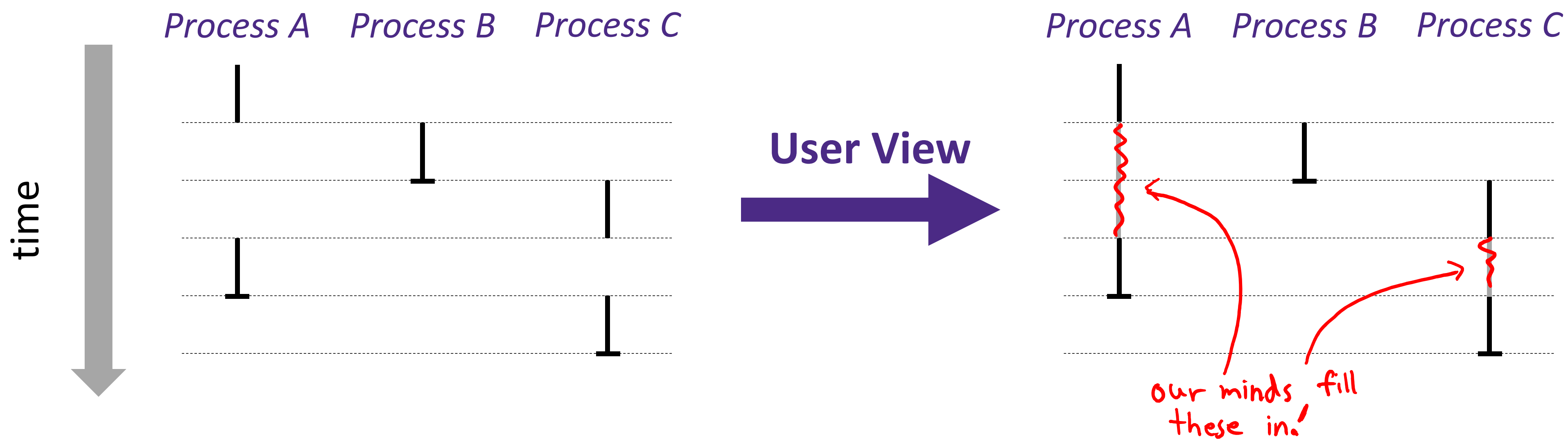


User's View of Concurrency

Assume only one CPU

- Control flows for concurrent processes are physically disjoint in time
  - CPU only executes instructions for one process at a time

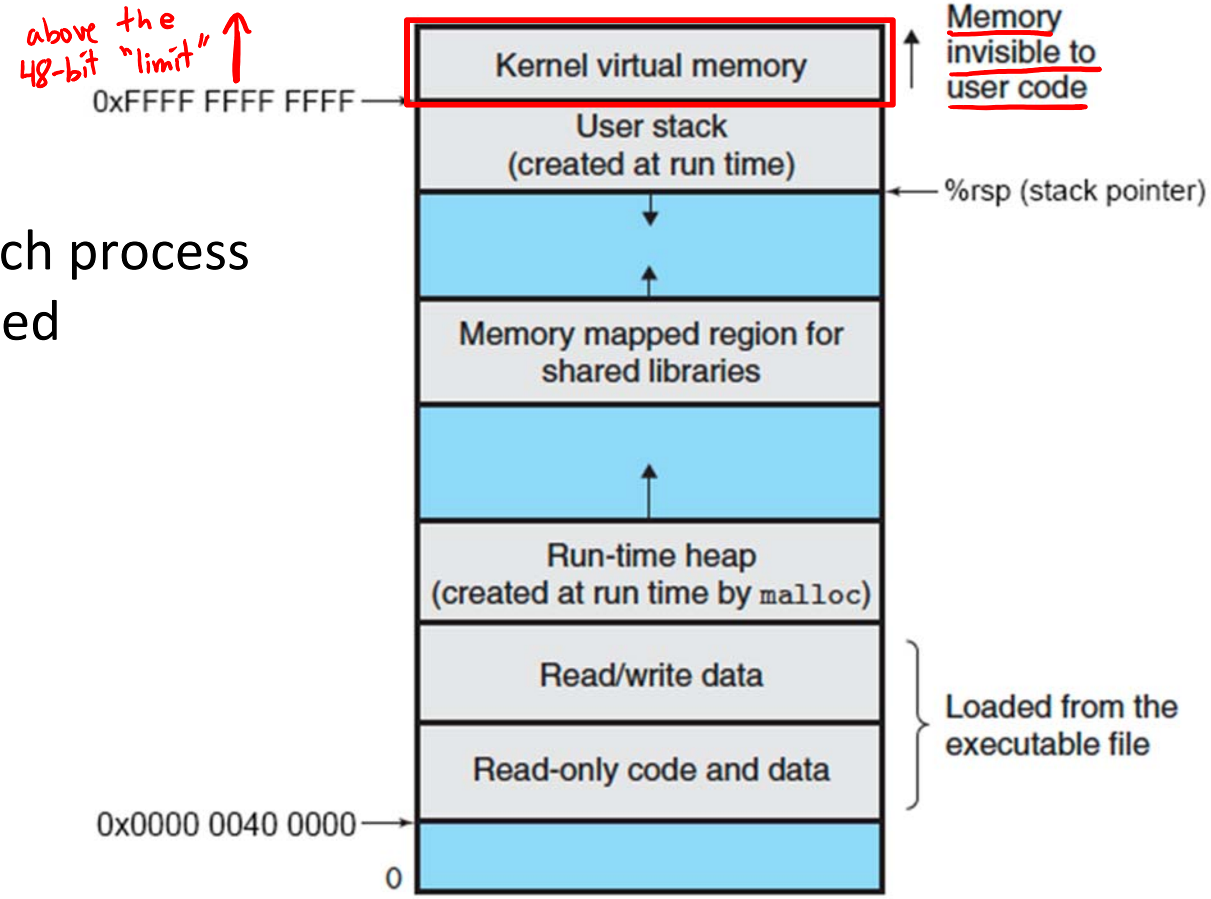
- However, the user can *think of* concurrent processes as executing at the same time, in *parallel*



Context Switching

Assume only one CPU

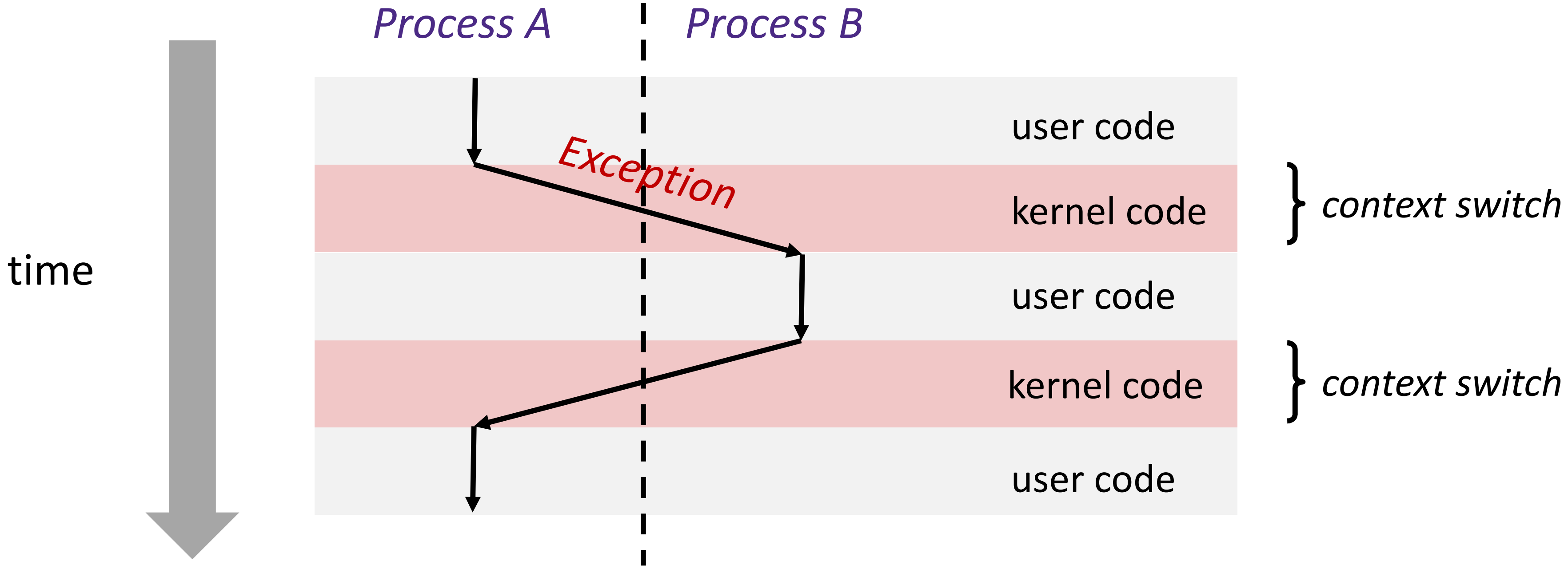
- Processes are managed by a *shared* chunk of OS code called the kernel
  - The kernel is not a separate process, but rather runs as part of a user process
- In x86-64 Linux:
  - Same address in each process refers to same shared memory location


above the 48-bit "limit"
0xFFFF FFFF FFFF
Kernel virtual memory
Memory invisible to user code
User stack (created at run time)
%rsp (stack pointer)
Memory mapped region for shared libraries
Run-time heap (created at run time by malloc)
Read/write data
Read-only code and data
Loaded from the executable file
0x0000 0040 0000
0

Context Switching

Assume only one CPU

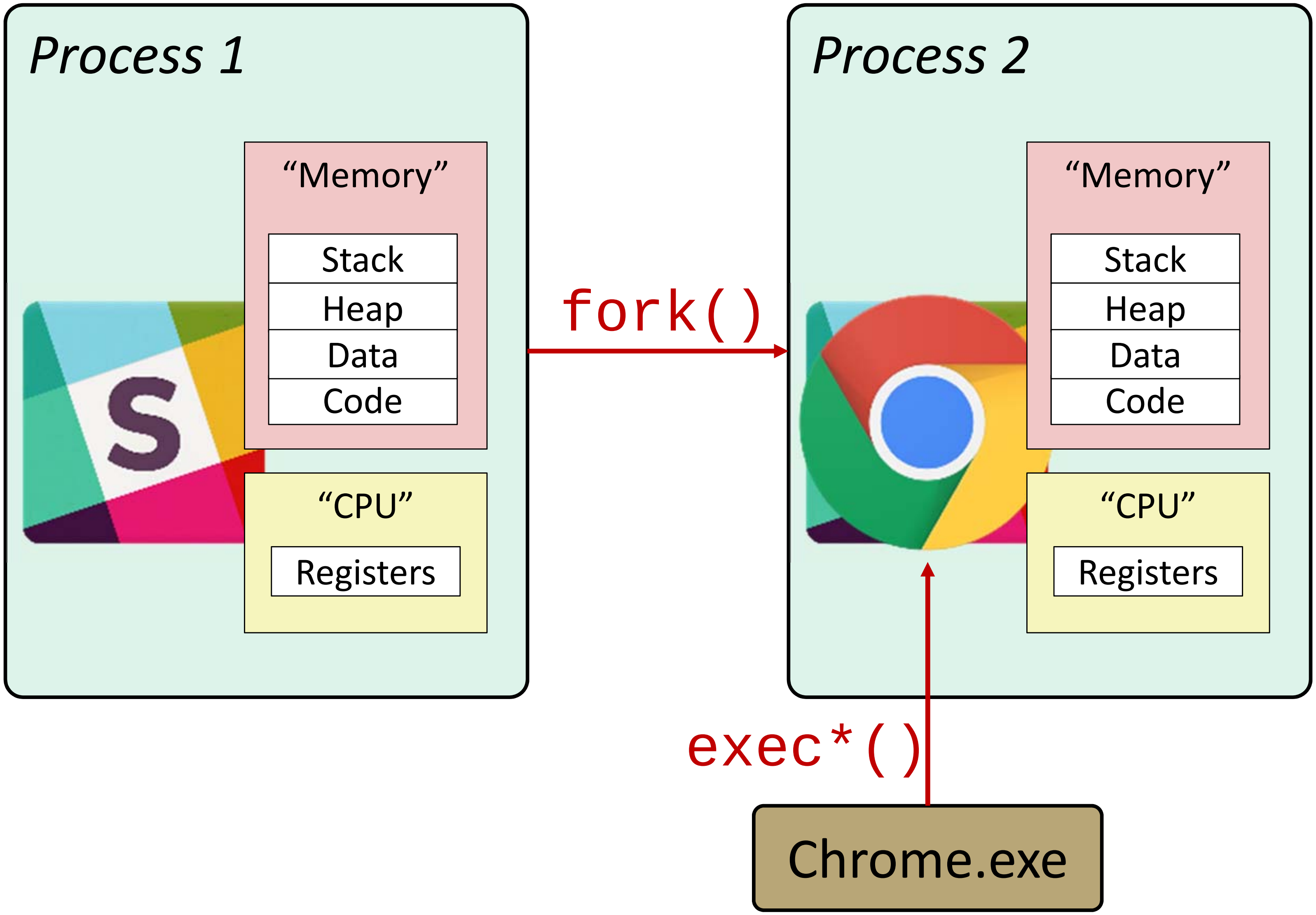
- Processes are managed by a *shared* chunk of OS code called the kernel
  - The kernel is not a separate process, but rather runs as part of a user process
- Context switch passes control flow from one process to another and is performed using kernel code



Processes

- Processes and context switching
- **Creating new processes**
  - **`fork()`, `exec*()`, and `wait()`**
- Zombies

Creating New Processes & Programs



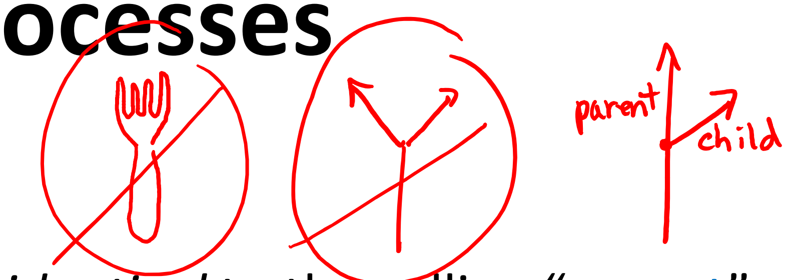
Creating New Processes & Programs

- fork-exec model (Linux):
  - `fork()` creates a copy of the current process
  - `exec*()` replaces the current process' code and address space with the code for a different program
    - Family: `execv`, `execl`, `execve`, `execle`, `execvp`, `execlp`
  - `fork()` and `execve()` are *system calls*

    ↳ intentional, synchronous exceptions ⇒ traps

- Other system calls for process management:
  - `getpid()`
  - `exit()`
  - `wait()`, `waitpid()`

fork: Creating New Processes



returns a PID

- `pid_t fork(void)`
  - Creates a new "child" process that is *identical* to the calling "parent" process, including all state (memory, registers, etc.)
  - Returns 0 to the child process
  - Returns child's process ID (PID) to the parent process

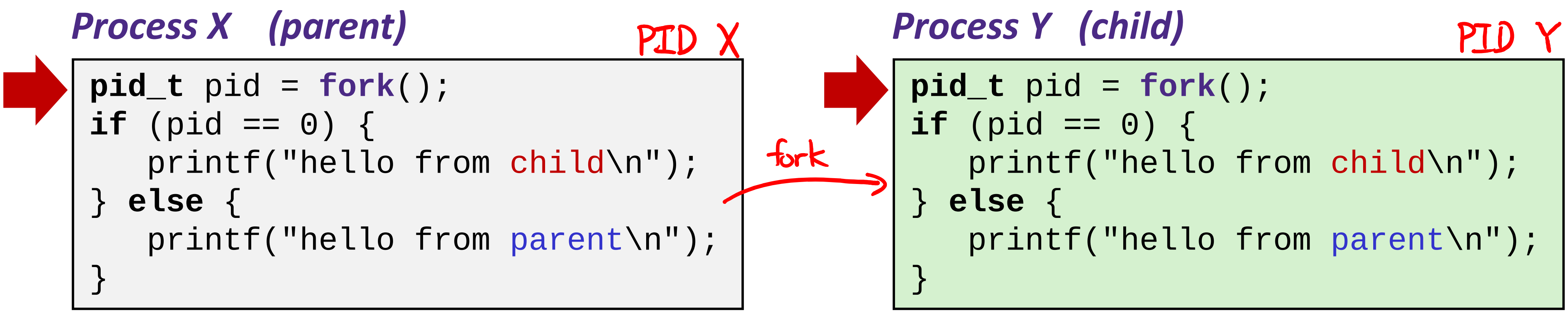
- Child is *almost* identical to parent:
  - Child gets an identical (but separate) copy of the parent's virtual address space
  - Child has a different PID than the parent

```
pid_t pid = fork();
if (pid == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

parent gets child's PID
child gets 0

- `fork` is unique (and often confusing) because it is called once but returns "twice"

Understanding fork



Process X (parent)

PID X

```
pid_t pid = fork();
if (pid == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

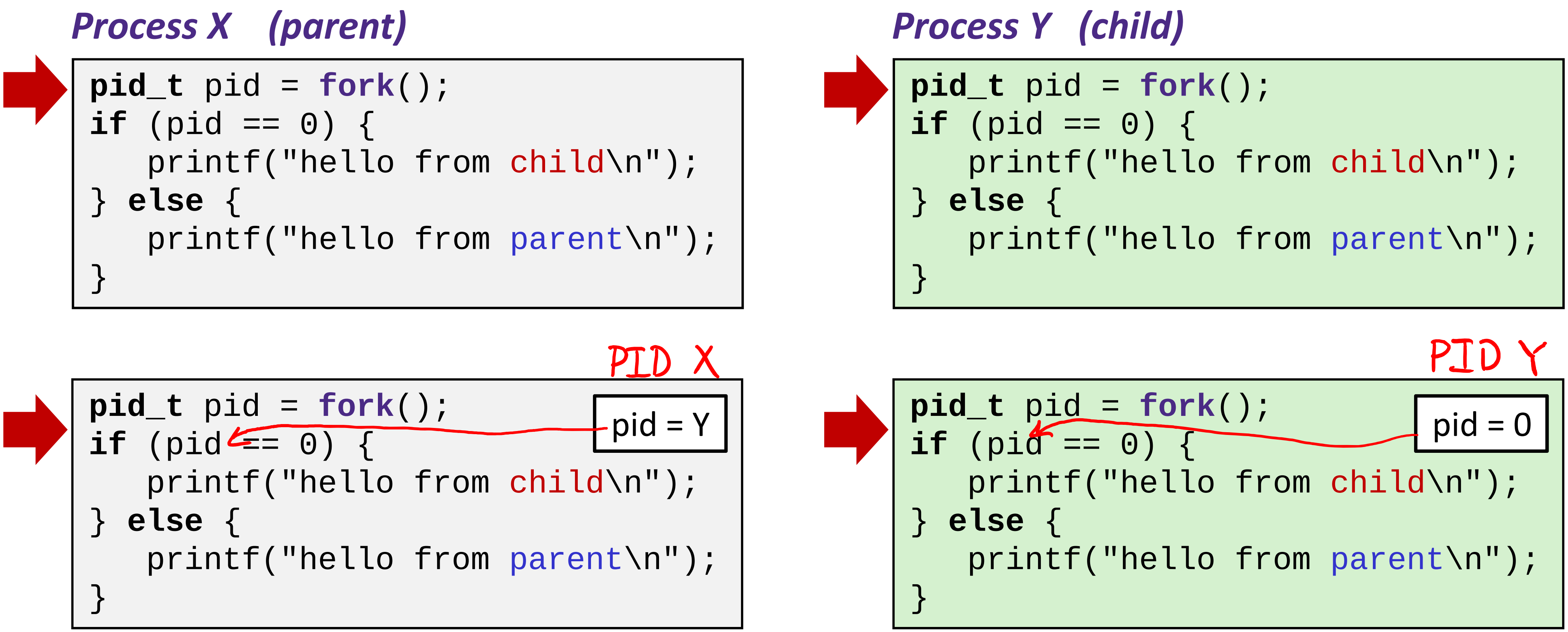
fork

Process Y (child)

PID Y

```
pid_t pid = fork();
if (pid == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

Understanding fork



Process X (parent)

```
pid_t pid = fork();
if (pid == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

PID X

```
pid_t pid = fork();
if (pid == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

pid = Y

Process Y (child)

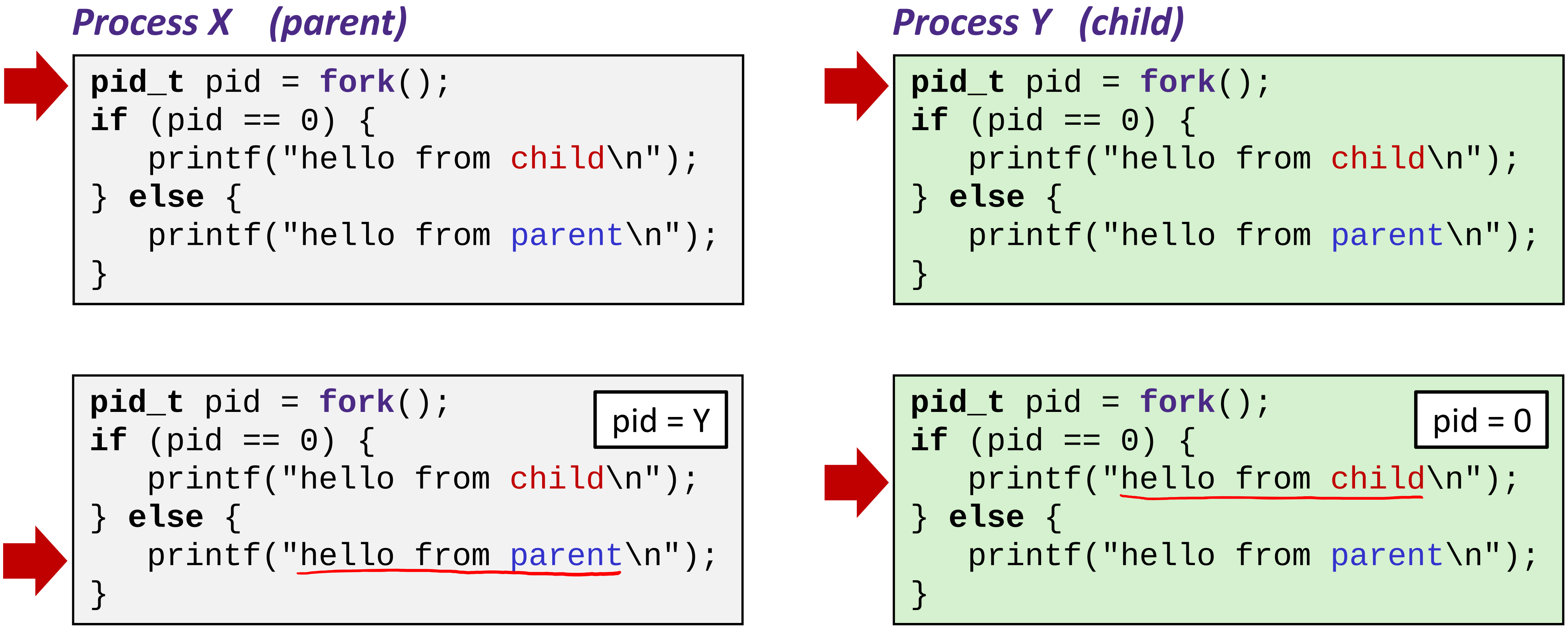
```
pid_t pid = fork();
if (pid == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

PID Y

```
pid_t pid = fork();
if (pid == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

pid = 0

Understanding fork



Process X (parent)

```
pid_t pid = fork();
if (pid == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

Process Y (child)

```
pid_t pid = fork();
if (pid == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

```
pid_t pid = fork();
if (pid == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

```
pid_t pid = fork();
if (pid == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

```
hello from parent
```

```
hello from child
```

Which one appears first?

non-deterministic!

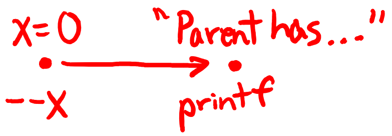
Fork Example

```
void fork1() {
    int x = 1;
    pid_t pid = fork();  ← splits here
    if (pid == 0)
        printf("Child has x = %d\n", ++x); ← child only
    else
        printf("Parent has x = %d\n", --x); ← parent only
    printf("Bye from process %d with x = %d\n", getpid(), x); ← both
}
```

- Both processes continue/start execution after `fork`
  - Child starts at instruction after the call to `fork` (storing into `pid`)
- Can't predict execution order of parent and child
- Both processes start with `x=1`
  - Subsequent changes to `x` are independent
- Shared open files: stdout is the same in both parent and child

Modeling `fork` with Process Graphs

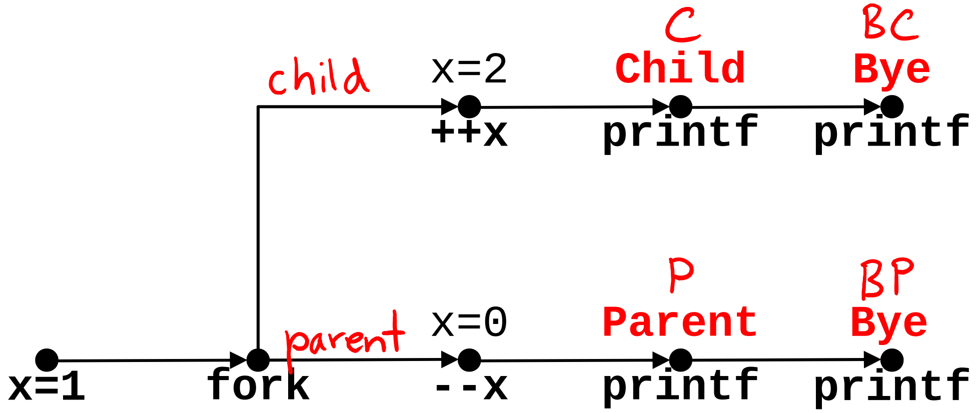
- A *process graph* is a useful tool for capturing the partial ordering of statements in a concurrent program
  - Each vertex is the execution of a statement
  - a → b means a happens before b
  - Edges can be labeled with current value of variables
  - `printf` vertices can be labeled with output
  - Each graph begins with a vertex with no inedges



- Any *topological sort* of the graph corresponds to a feasible total ordering
  - Total ordering of vertices where all edges point from left to right

Fork Example: Possible Output

```
void fork1() {
    int x = 1;
    pid_t pid = fork();
    if (pid == 0)
        printf("Child has x = %d\n", ++x);
    else
        printf("Parent has x = %d\n", --x);
    printf("Bye from process %d with x = %d\n", getpid(), x);
}
```



Possible

C BC P BP

P BP C BP

C P BC BP

C P BP BC

etc...

Not Possible

C BC BP P

P BC C BP

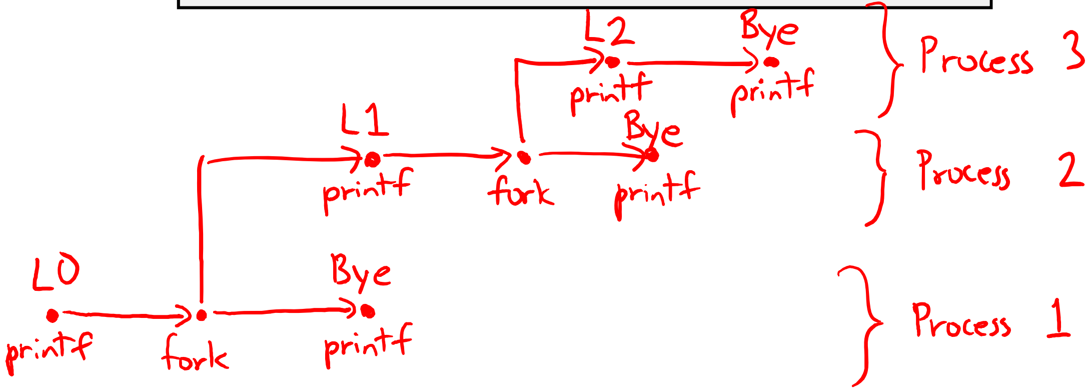
etc...

as long as C comes before BC
and P comes before BP

Peer Instruction Question

- Are the following sequences of outputs possible?
  - Vote at http://PollEv.com/justinh

```
void nestedfork() {
    printf("L0\n");
    if (fork() == 0) {
        printf("L1\n");
        if (fork() == 0) {
            printf("L2\n");
        }
    }
    printf("Bye\n");
}
```



Seq 1:	Seq 2:	
L0	L0	← Process 1
L1	Bye	← Process 1
Bye	L1	← Process 2
Bye	L2	← Process 3
Bye	Bye	← Process 2/3
L2 !	Bye	← Process 3/2

	Seq 1	Seq 2
A.	No	No
[✓ B.]	No	Yes
C.	Yes	No
D.	Yes	Yes
E.	We're lost…	

Fork-Exec

Note: the return values of fork and exec* should be checked for errors

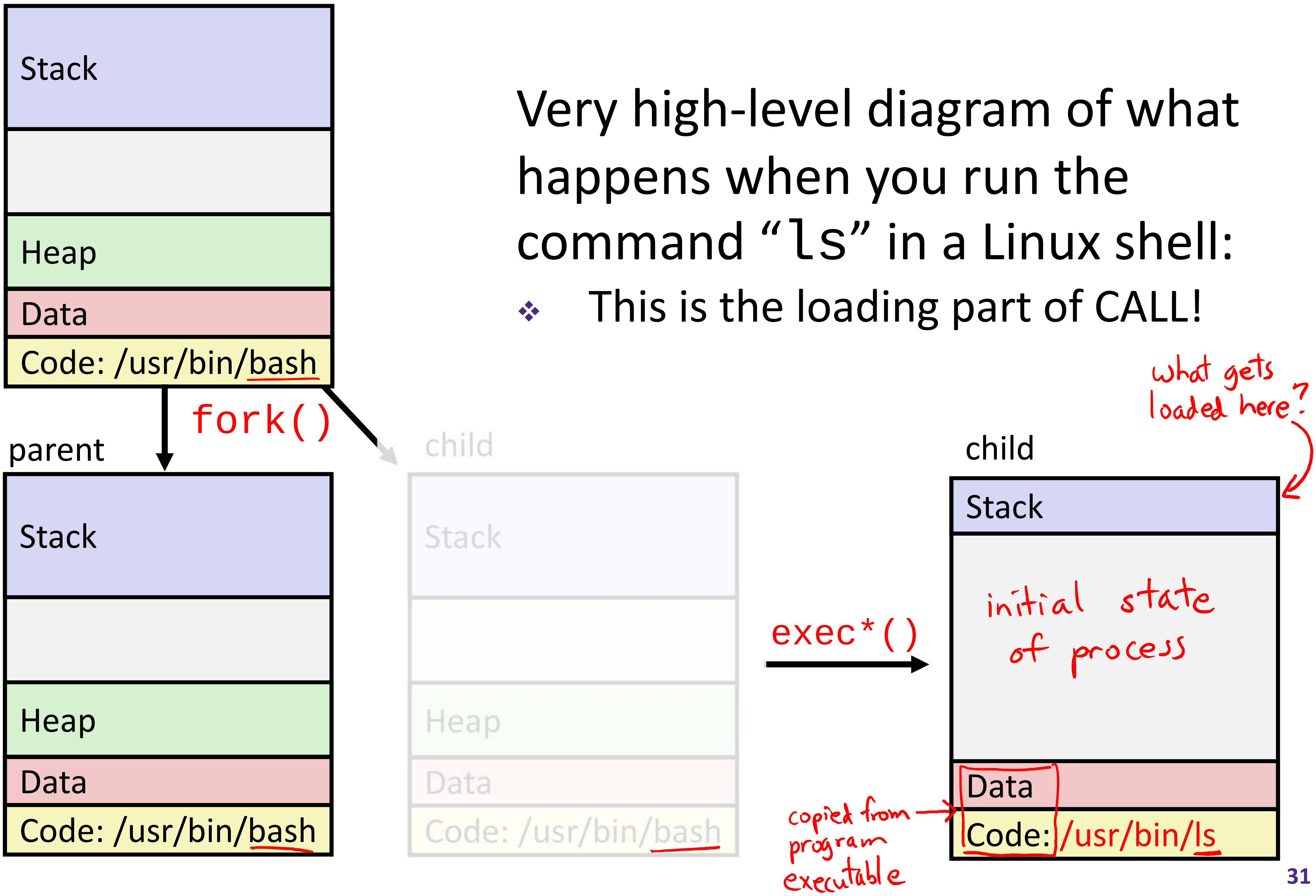
- fork-exec model:
  - fork() creates a copy of the current process
  - exec*() replaces the current process' code and address space with the code for a different program
    - Whole family of exec calls – see **exec(3)** and **execve(2)**

```
// Example arguments: path="/usr/bin/ls",
//     argv[0]="/usr/bin/ls", argv[1]="-ahl", argv[2]=NULL
void fork_exec(char *path, char *argv[]) {
   pid_t pid = fork();
   if (pid != 0) {
      printf("Parent: created a child %d\n", pid);
   } else {
      printf("Child: about to exec a new program\n");
      execv(path, argv);
   }
   printf("This line printed by parent only!\n");
}
```

Exec-ing a new program

Very high-level diagram of what happens when you run the command "`ls`" in a Linux shell:

- This is the loading part of CALL!



execve Example

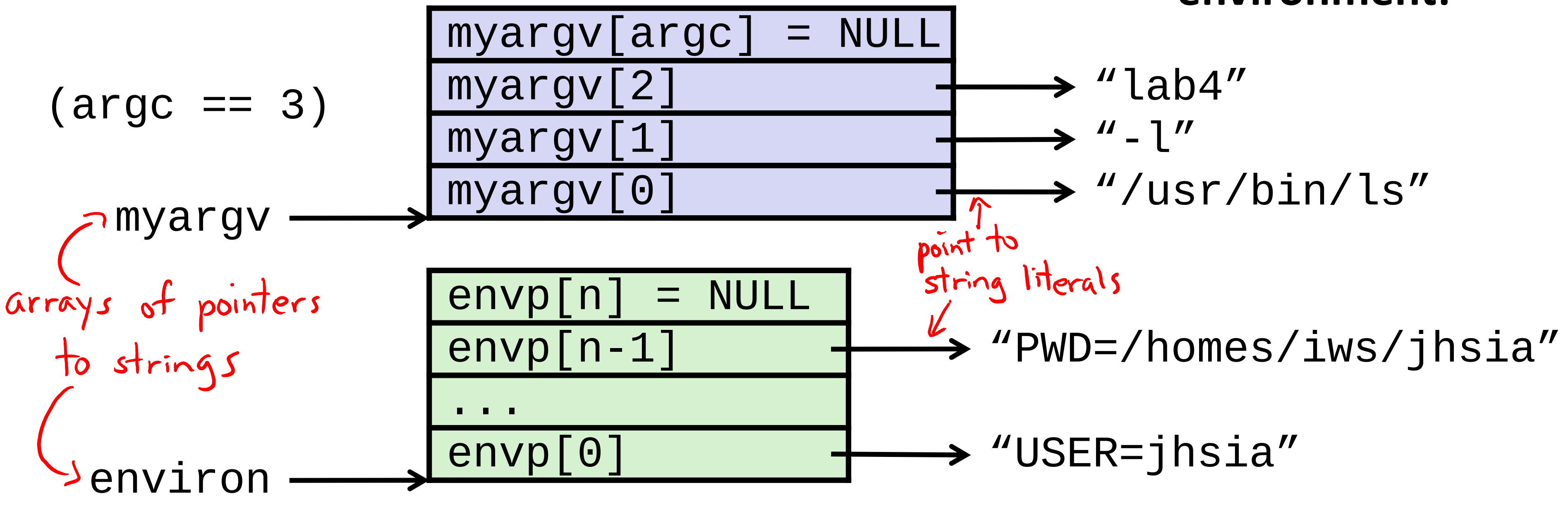
int main(int argc, char* argv[])

get command-line arguments into program

This is extra (non-testable) material

arguments

Execute "/usr/bin/ls -l lab4" in child process using current environment:



(argc == 3)

myargv

myargv[argc] = NULL

myargv[2] → "lab4"

myargv[1] → "-l"

myargv[0] → "/usr/bin/ls"

point to string literals

arrays of pointers to strings

environ

envp[n] = NULL

envp[n-1] → "PWD=/homes/iws/jhsia"

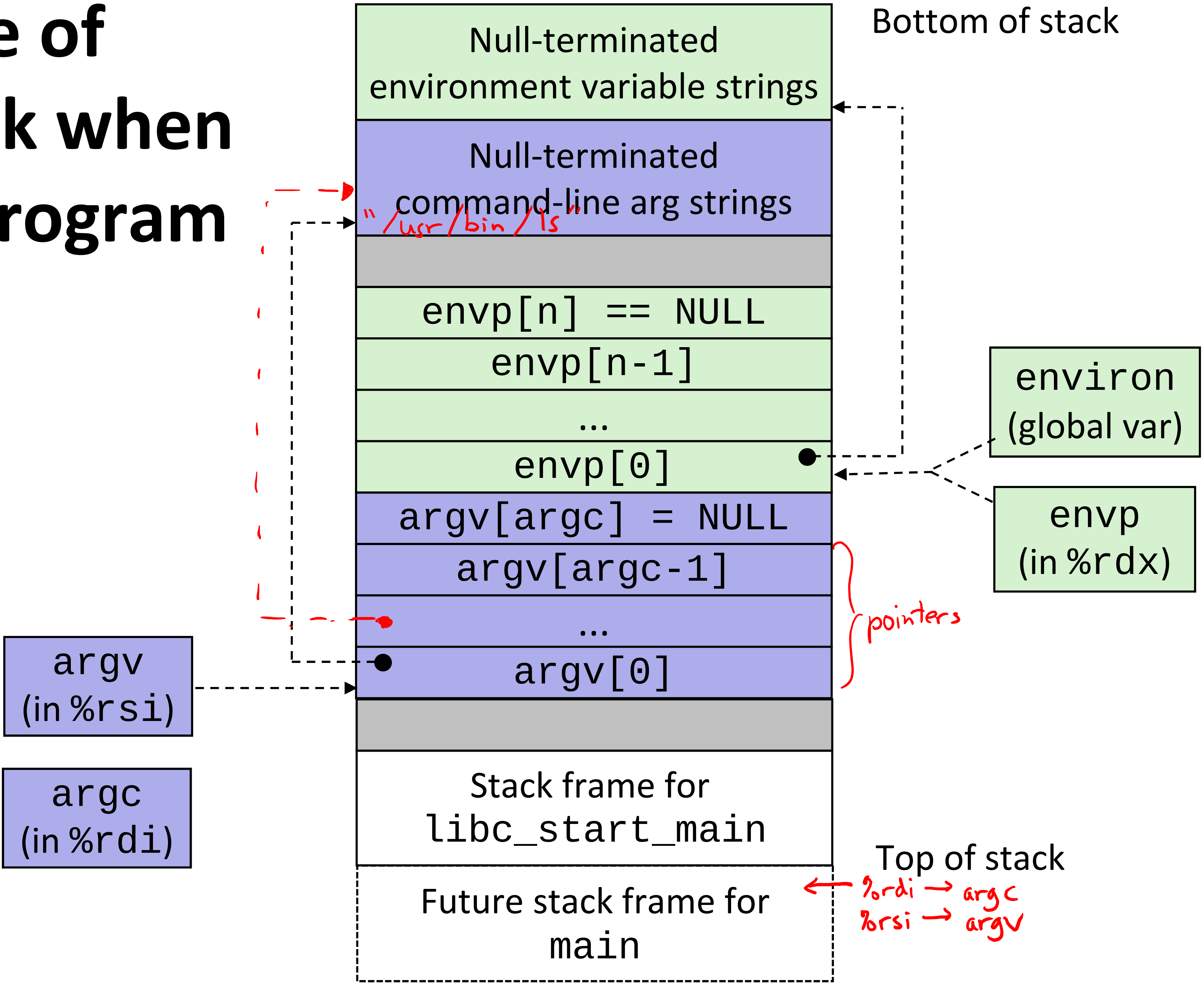
...

envp[0] → "USER=jhsia"

```
if ((pid = fork()) == 0) {   /* Child runs program */
   if (execve(myargv[0], myargv, environ) < 0) {
      printf("%s: Command not found.\n", myargv[0]);
      exit(1);
   }
}
```

Run the `printenv` command in a Linux shell to see your own environment variables

Structure of the Stack when a new program starts



Bottom of stack

Null-terminated environment variable strings

Null-terminated command-line arg strings

"/usr/bin/ls"

envp[n] == NULL

envp[n-1]

...

envp[0]

argv[argc] = NULL

argv[argc-1]

...

argv[0]

pointers

Stack frame for libc_start_main

Future stack frame for main

Top of stack

%rdi → argc

%rsi → argv

environ (global var)

envp (in %rdx)

argv (in %rsi)

argc (in %rdi)

This is extra (non-testable) material

`exit`: Ending a process

- `void exit(int status)`
  - Exits a process
    - Status code: 0 is used for a normal exit, nonzero for abnormal exit

Processes

- Processes and context switching
- Creating new processes
  - `fork()`, `exec*()`, and `wait()`
- **Zombies**

Zombies

- When a process terminates, it still consumes system resources
  - Various tables maintained by OS
  - Called a "zombie" (a living corpse, half alive and half dead)

- *Reaping* is performed by parent on terminated child
  - Parent is given exit status information and kernel then deletes zombie child process

- What if parent doesn't reap?
  - If any parent terminates without reaping a child, then the orphaned child will be reaped by `init` process (pid == 1)
    - **Note:** on more recent Linux systems, `init` has been renamed `systemd`
  - In long-running processes (e.g. shells, servers) we need *explicit* reaping

`wait`: Synchronizing with Children

- **`int`** `wait(`**`int`** `*child_status)`
  - Suspends current process (*i.e.* the parent) until one of its children terminates
  - Return value is the PID of the child process that terminated
    - *On successful return, the child process is reaped*
  - If `child_status != NULL`, then the `*child_status` value indicates why the child process terminated
    - Special macros for interpreting this status – see **`man wait(2)`**
- **Note:** If parent process has multiple children, `wait` will return when *any* of the children terminates
  - `waitpid` can be used to wait on a specific child process

wait: Synchronizing with Children

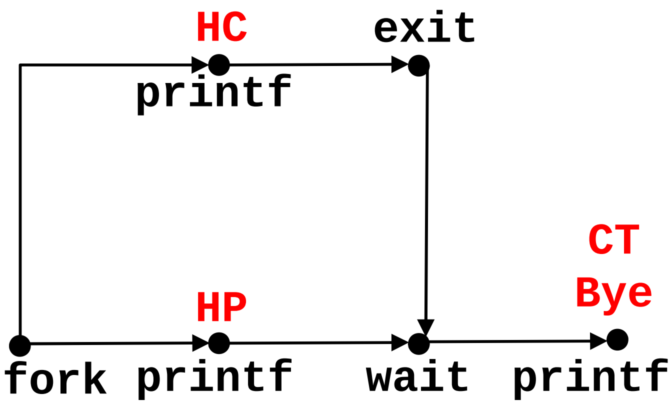
```
void fork_wait() {
   int child_status;

   if (fork() == 0) {
      printf("HC: hello from child\n");
      exit(0);
   } else {
      printf("HP: hello from parent\n");
      wait(&child_status);
      printf("CT: child has terminated\n");
   }
   printf("Bye\n");
}
```

forks.c

child

parent



Feasible output:

HC
HP
CT
Bye

HP
HC
CT
Bye

Infeasible output:

HP
CT
Bye
HC

Example: Zombie

```
void fork7() {
   if (fork() == 0) {
      /* Child */
      printf("Terminating Child, PID = %d\n",
             getpid());
      exit(0);
   } else {
      printf("Running Parent, PID = %d\n",
             getpid());
      while (1); /* Infinite loop */
   }
}
```

parent persists

forks.c

```
linux> ./forks 7 &
[1] 6639
Running Parent, PID = 6639
Terminating Child, PID = 6640
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6639 ttyp9    00:00:03 forks
 6640 ttyp9    00:00:00 forks <defunct>
 6641 ttyp9    00:00:00 ps
linux> kill 6639
[1]    Terminated
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6642 ttyp9    00:00:00 ps
```

parent

child

- ps shows child process as "defunct"
- Killing parent allows child to be reaped by `init`

Example: Non-terminating Child

```
void fork8() {
   if (fork() == 0) {
      /* Child */
      printf("Running Child, PID = %d\n",
             getpid());
      while (1); /* Infinite loop */
   } else {
      printf("Terminating Parent, PID = %d\n",
             getpid());
      exit(0);
   }
}
```

child persists

forks.c

```
linux> ./forks 8
Terminating Parent, PID = 6675
Running Child, PID = 6676
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6676 ttyp9    00:00:06 forks
 6677 ttyp9    00:00:00 ps
linux> kill 6676
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6678 ttyp9    00:00:00 ps
```

- Child process still active even though parent has terminated
- Must kill explicitly, or else will keep running indefinitely

Process Management Summary

- `fork` makes two copies of the same process (parent & child)
  - Returns different values to the two processes
- `exec*` replaces current process from file (new program)
  - Two-process program:
    - First `fork()`
    - **if** (pid == 0) { */* child code */* } **else** { */* parent code */* }
  - Two different programs:
    - First `fork()`
    - **if** (pid == 0) { execv(…) } **else** { */* parent code */* }

- `wait` or `waitpid` used to synchronize parent/child execution and to reap child process

Summary

- Processes
  - At any given time, system has multiple active processes
  - On a one-CPU system, only one can execute at a time, but each process appears to have total control of the processor
  - OS periodically "context switches" between active processes
    - Implemented using *exceptional control flow*
- Process management
  - `fork`: one call, two returns
  - `execve`: one call, usually no return
  - `wait` or `waitpid`: synchronization
  - `exit`: one call, no return

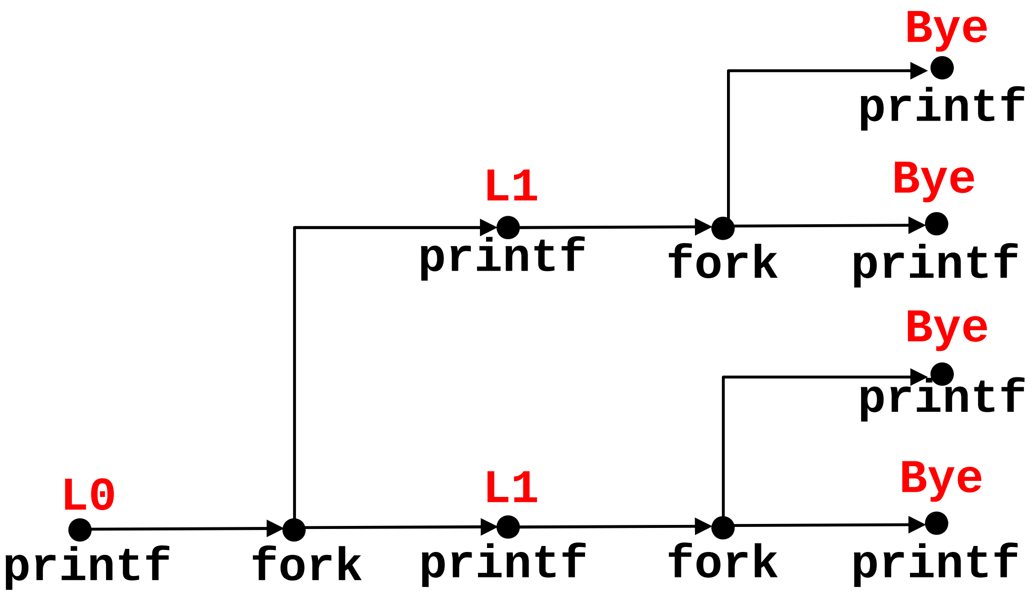
BONUS SLIDES

Detailed examples:

- Consecutive forks
- `wait()` example
- `waitpid()` example

Example: Two consecutive `fork`s

```
void fork2() {
   printf("L0\n");
   fork();
   printf("L1\n");
   fork();
   printf("Bye\n");
}
```



Feasible output:

L0
L1
Bye
Bye
L1
Bye
Bye

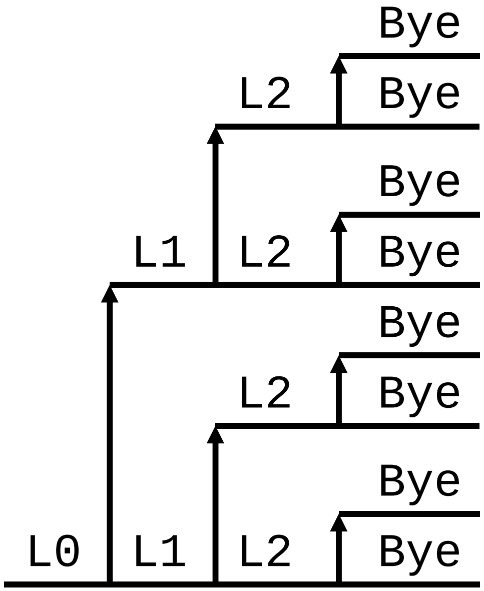
Infeasible output:

L0
Bye
L1
Bye
L1
Bye
Bye

Example: Three consecutive `fork`s

- Both parent and child can continue forking

```
void fork3() {
    printf("L0\n");
    fork();
    printf("L1\n");
    fork();
    printf("L2\n");
    fork();
    printf("Bye\n");
}
```



wait() Example

- If multiple children completed, will take in arbitrary order
- Can use macros WIFEXITED and WEXITSTATUS to get information about exit status

```
void fork10() {
   pid_t pid[N];
   int i;
   int child_status;
   for (i = 0; i < N; i++)
      if ((pid[i] = fork()) == 0)
         exit(100+i); /* Child */
   for (i = 0; i < N; i++) {
      pid_t wpid = wait(&child_status);
      if (WIFEXITED(child_status))
         printf("Child %d terminated with exit status %d\n",
                wpid, WEXITSTATUS(child_status));
      else
         printf("Child %d terminated abnormally\n", wpid);
   }
}
```

waitpid(): Waiting for a Specific Process

```
pid_t waitpid(pid_t pid, int &status, int options)
```

- suspends current process until specific process terminates
- various options (that we won’t talk about)

```
void fork11() {
   pid_t pid[N];
   int i;
   int child_status;
   for (i = 0; i < N; i++)
      if ((pid[i] = fork()) == 0)
         exit(100+i); /* Child */
   for (i = 0; i < N; i++) {
      pid_t wpid = waitpid(pid[i], &child_status, 0);
      if (WIFEXITED(child_status))
         printf("Child %d terminated with exit status %d\n",
                wpid, WEXITSTATUS(child_status));
      else
         printf("Child %d terminated abnormally\n", wpid);
   }
}
```